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WEIGHT AND VOLUME ESTIMATES FOR ALUMINUM-AIR BATTERIES DESIGNED FOR ELECTRIC VEHICLE APPLICATIONS

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ABSTRACT*

The weights and volumes of the reactants, electrolyte, and hardware components are estimated for an aluminum-air battery designed for a 40-kW (peak), 70-kWh aluminum-air battery. Generalized equations are derived which express battery power and energy content as functions of total anode area, aluminum-anode weight, and discharge current density. Equations are also presented which express total battery weight and volume as linear combinations of the variables, anode area and anode weight. The sizing and placement of battery components within the engine compartment of typical five-passenger vehicles is briefly discussed.

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INTRODUCTION

The purpose of this study is to develop a set of generalized equations which express battery energy, power, weight, and volume as functions of three system design parameters: total anode area, aluminum anode weight, and a parameter indicating the relative frequencies of the aluminum and water refueling operations. Equations of this nature are useful in matching the electrical characteristics of a battery system to the overall energy and power requirements of a vehicle of generalized design, and for the subsequent calculations of vehicle weight and energy consumption. The data on which these equations are based come from three sources: the intensive properties of laboratory aluminum-air single cells; measurements or estimates of the weights and volumes of certain hardware components; and estimates of overall reaction stoichiometry based on computer modelling of mass and enthalpy flows within a battery under specified operating conditions.

The system chosen for analysis is shown in Figure 1. This design provides for the filtering and scrubbing of the air intake; for saturation of air with water vapor at temperatures near to the operating temperature of $60^{o}C$; and for condensing water from the air-cathode exhaust for subsequent use as a battery reactant. The battery is provided with a crystallizer to allow decomposition of the battery intermediate reaction product (a sodium aluminate solution) into the solid hydrargillite:

$$NaAl(OH)_4 = Al(OH)_3 + NaOH_{aq} \qquad (1)$$

The design of this process has been reported.[1] The crystalline product is washed in distilled water, and drained under a pressure difference of 10 kPa (1.5 psi) to yield a product containing 14%-wt water.

The relative weights of aluminum and water have been computed as part of a comprehensive mass and enthalpy balance performed for a generalized design. In particular, the design depicted in Figure 1 was evaluated for the following (time-average) operating conditions: ambient temperature, $27^{o}C$; current density, 1.3 kA/m^2; operating temperature, $60^{o}C$; and for a total oxygen throughput equal to 4.88 times the stoichiometric consumption rate. Although the stoichiometry of the net cell reaction,

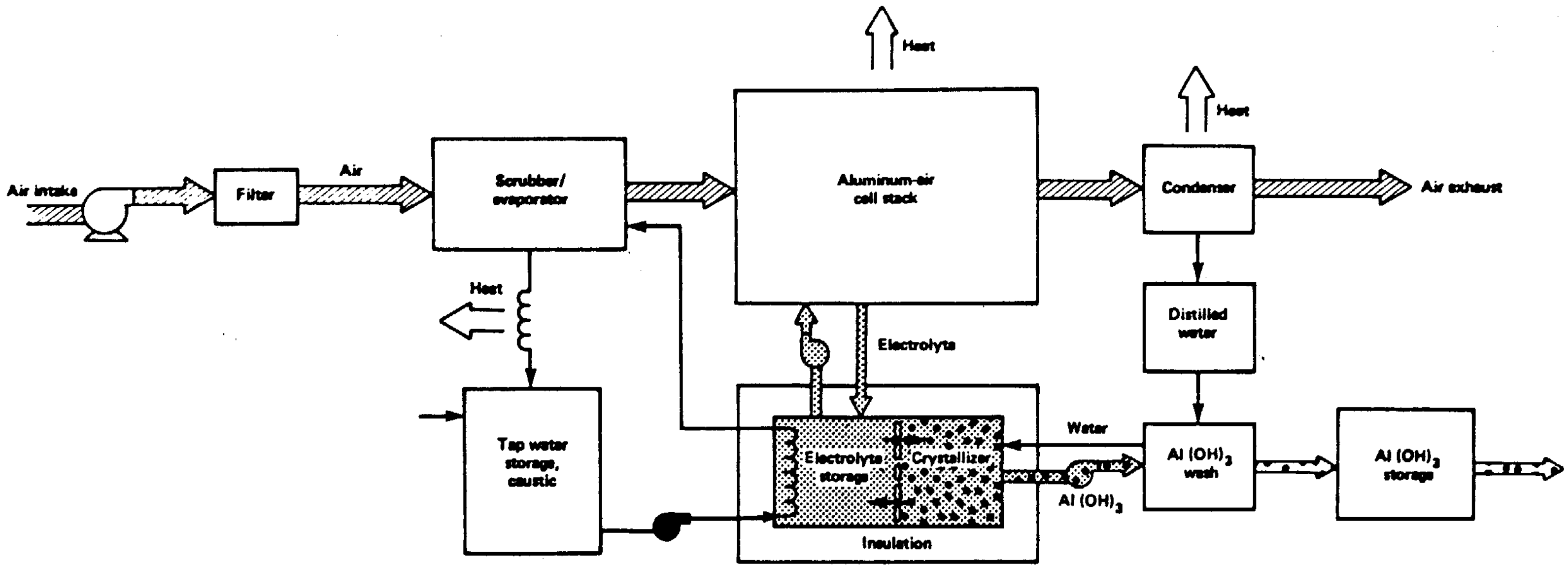

Figure 1. Aluminum-air power cell system. This design allows distillation of tap water to provide for the battery reaction. The reaction product (a polymorph of aluminum hydroxide called "hydrargillite") is crystallized in an auxiliary component and processed into a water-washed, drained, granular product for eventual removal and recycling.

$$Al + 3/2\ H_2O + 3/4\ O_2 = Al(OH)_3 \tag{2}$$

predicts that 1.0 kg of water should be consumed per kilogram of aluminum, the actual quantity is larger (1.5 kg) because of the combined losses due to evaporation, entrapment in voids in the hydrargillite product, and consumption through the parasitic corrosion of aluminum.

Volume and Weight Estimates of a 40 kW, 70 kWh Battery

The weights and volume estimates for a 40 kW, 70-kWh battery are summarized in Table 1 and listed in more detail in the Appendix. This peak power and energy capacity were chosen to provide a 1300-kg (gross) vehicle with a range of 400 km and a power/weight ratio of 30 W/kg. In this case, sufficient aluminum is provided for an extended range of 1600 km, while the actual range of the vehicle is determined by the inventory of tap water. The tap water requirements have been enhanced by 25% in accordance with the traditional definition of vehicle range: distance traveled at 80% fuel exhaustion. Thus a battery with a "nominal" energy content of 70 kWh will deliver 25% more energy (88 kWh) upon exhaustion of the limiting reactant (water). The aluminum inventory for 1600 km has also been enhanced by 25% to facilitate recharging. It is assumed that hydrargillite is removed from the battery at an average frequency of once for each 400 km of travel, although the volume of the storage tank would suffice for 600 km.

Because of losses of water by evaporation and the continuous absorption of oxygen from the air by the battery during discharge, the initial and final weights of the battery will differ by about 10 kg. Also, the total weight of aluminum (metal plus hydrargillite) decreases stepwise during each hydrargillite withdrawl. These effects have been taken into consideration in calculating time-average reactant weights.

The total battery weight for this particular design and fueling schedule is 232 kg. The energy content (based on water as the limiting reactant and a gross energy yield of aluminum of 4.25 kWh/kg) is 68.5 kWh, and the short-duration peak power is 37 kW. With increased additions of tap water, the energy content would increase at the rate of 2.7 kWh/liter.

Table 1. Summary of Component Weights and Volumes for a 40-kW, 70-kWh Electric Vehicle Battery

Components with scaling proportional to W^o_{Al}:	Weight, kg	Volume, dm^3
Reactants and products	82	--[a]
Tap water and $Al(OH)_3$ storage tanks	4	114
Anode compartment of cell stack (excluding reserve)[b]	6	25[a]
Components with scaling proportional to A_a:		
Anode reserve and compartment[b]	18	6[a]
Distilled water surge tank	0.4	10
Crystallizer and electrolyte storage unit	24	78
Electrolyte	37	--[a]
Air filter and scrubbing system	2.2	17
Motors and pumps	8.6	2.8
Galvanic cell stack and air/electrolyte manifolding[b]	30	135[a]
Condenser	5	20
Miscellaneous (current busses, controls & sensors, etc.)	15	5[a]
	232	413

a Volumes of these components are wholly or partially counted in listing elsewhere in this column.

b The total galvanic cell stack and manifold weight (empty) and volume are 37 kg and 166 dm^3, respectively. Weight excludes reactants, electrolyte, and current busses external to cell stack. Part of this total weight and volume have been attributed to the compartments for the aluminum anode, prorated according to the ratio of metal volume to cell stack volume.

Different levels of confidence may be assigned to the estimates for the various components and reactants in the Appendix. The weights of the reactants reflect measured quantities and stoichiometric relationships, and are likely to be accurate within $\pm$ 10%. Data given for the tanks, air subsystem, and motors are also likely to be accurate, as these represent available components. The crystallizer design reflects scale requirements derived from the kinetics of the corresponding industrial process. The cell stack, however, has not been developed, and weight estimates are highly conjectural. We have excluded at this time the weight of a 600 W secondary battery required for start-up and shut-down power.

Generalized Equations for Battery Energy, Power, Weight and Volume

The above calculations of weight and power may be generalized for a battery of arbitrary power and energy capacity. For a given set of operating conditions, net battery power (P_b) and net energy capacity (E_b) may be expressed as functions of current density (i), total anode area (A_a), and the total mass of aluminum available for consumption (given limitations in supply of water), W^o_{Al}:

$$P_b = e_p \,(iV)\, A_a \tag{2}$$

$$E_b = e_p \,(e_c V\, F/W_{eq})\; W^o_{Al} \tag{3}$$

where e_p is the ratio of net to gross battery power, and corrects for internal power requirements of battery auxiliaries; e_c is the coulombic efficiency of aluminum dissolution (a function of current density and operating conditions); V is cell voltage measured at the terminals; F is the Faraday constant (96500 coul/eq) and W_{eq} is the equivalent weight of aluminum (9 g/g-eq).

The quantities in parentheses in equations (2) and (3) are the surface power density, p, and energy yield of aluminum, $\overline{E}_{Al}$, respectively:

$$p = iV \tag{4}$$

$$\overline{E}_{Al} = e_c VF/W_{eq} \tag{5}$$

Cell voltage varies with current density and depends on the composition and temperature of the electrolyte and on the size of interelectrode gap. Functional dependencies of V and e_c on operating conditions are shown in Figures 2 and 3. Rather than expand equations (4) and (5) to include the explicit dependence of voltage and coulombic efficiencies on operating conditions, we will limit our discussion below to two characteristic operating points. These are: conditions of peak power and of peak energy yield per unit of aluminum consumption.

As suggested in Table 1, the various components are required in quantities which are proportional to either the mass of aluminum, W^o_{Al}, or to the total surface area of the anodes, A_a. It is convenient to express the total weight of the battery, W_B, and volume, V_B, as linear combinations of the design variables W^o_{Al} and A_a:

$$W_b = K_1 W^o_{Al} + K_2 A_a , \quad (6)$$

$$V_b = K_3 W^o_{Al} + K_4 A_a . \quad (7)$$

Values of the proportionality constants are given in Table 2, and are expressed as functions of the parameter, n. This parameter is the ratio of an energy content (based on aluminum weight) to the actual energy content (as limited by the quantity of tap water). The ratio also indicates the relative mileage intervals between aluminum anode replacement and water replenishment.

By combining equations (6) and (7) with equations (2-5), we obtain relationships between battery weight (or volume) and energy content and power:

$$W_b = K_1 \, E_b/e_p\bar{E}_{Al} + K_2 P_b/e_p p \quad (8)$$

$$V_b = K_3 \, E_b/e_p\bar{E}_{Al} + K_4 P_b/e_p p \quad (9)$$

Each term must be evaluated with a consistent set of operating conditions. Battery weight and volume are plotted as functions of energy content (at peak energy yield) and peak power in Figure 4 for the case n = 4, $\bar{E}_{Al}$ = 4.25 kWh/kg, p = 6.2 kW/m^2, and e_p = 0.96 and 1.0 for nominal and peak-power conditions. (Auxiliaries are powered by a secondary battery during peak power conditions.)

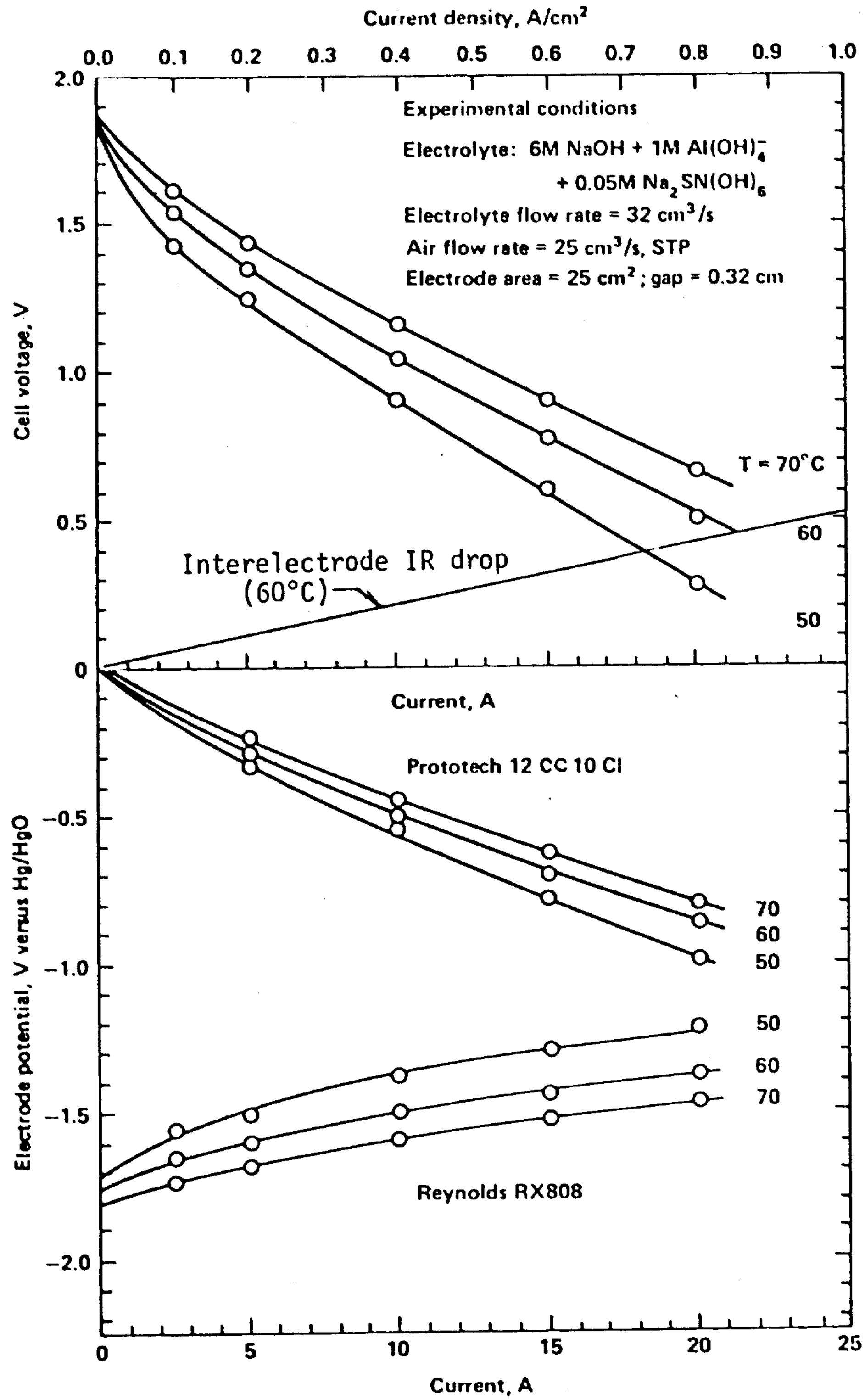

Figure 2. Dependence of cell voltage and electrode potentials (uncorrected for IR drop) on current density for Reynolds alloy RX808 and Prototech fabric electrode. Interelectrode IR drop is substantial because of low electrolyte conductivity (0.6 $ohm^{-1}cm^{-1}$ at $60^{o}C$).

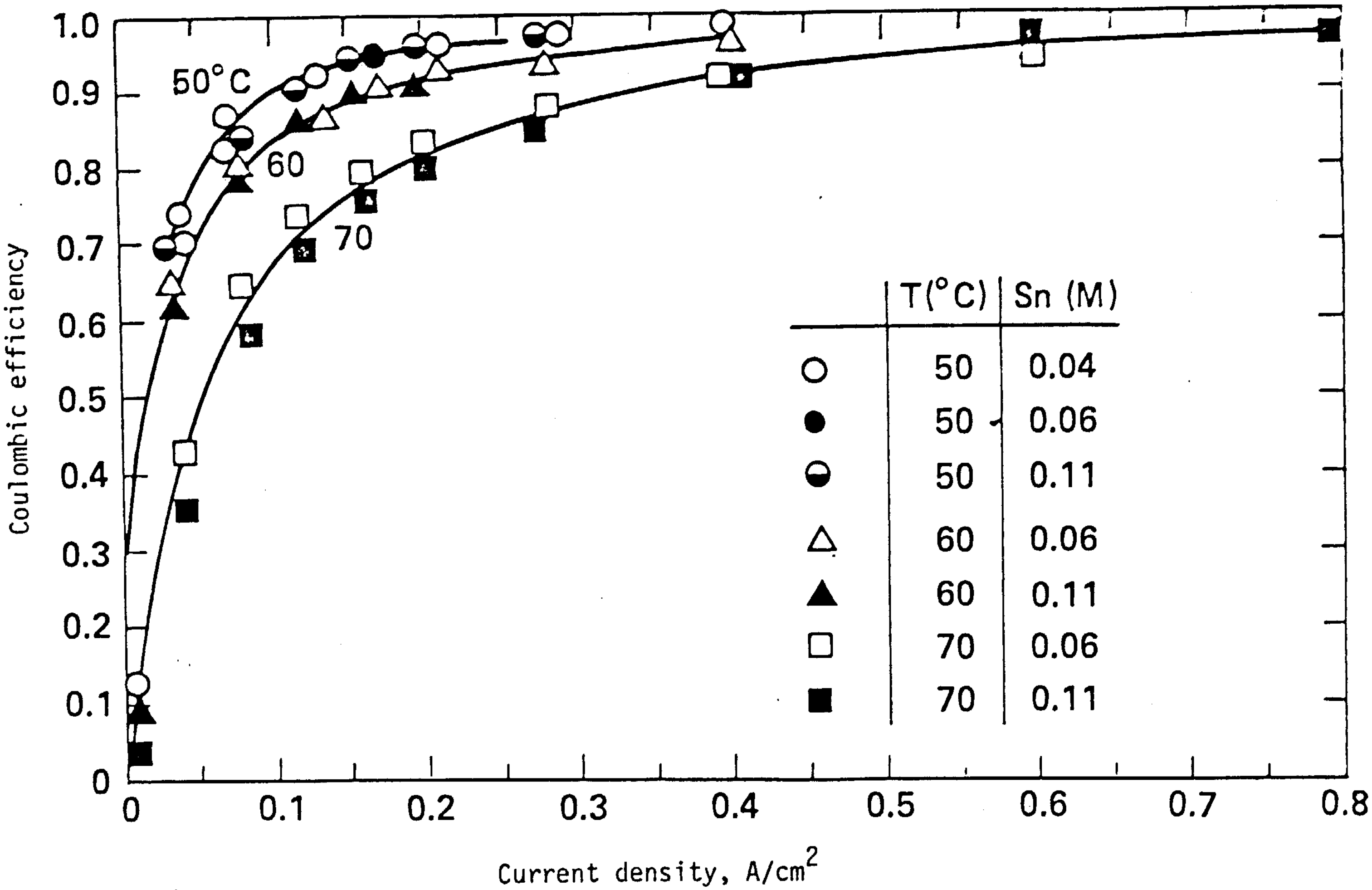

Figure 3. Coulombic efficiency of anodic dissolution of aluminum alloy RX808 in caustic-aluminate electrolytes. Electrolyte composition: 6M NaOH + 1M $Al(OH)_3$ + 0.04-0.11M $Na_2Sn(OH)_6$; Flow rate 30-100 ml/s (Re = 800-3500); electrode area = 25 cm^2; interelectrode gap = 0.32 cm.

Table 2. Coefficients of Aluminum Weight W^{o}_{Al} and Anode Area A_a in Generalized Equations for Battery Weight and Volume[a]

Coefficient	Units	Value[b]
K_1	---	3.1 + 0.58n
K_2	kg/m^2	23
K_3	dm^3/kg	6.8 + 0.37n
K_4	dm^3/m^2	46

[a] Coefficients reflect time-average values.

[b] n is the ratio of energy capacity (as limited by the quantity of aluminum) to the energy capacity (as limited by the quantity of water).

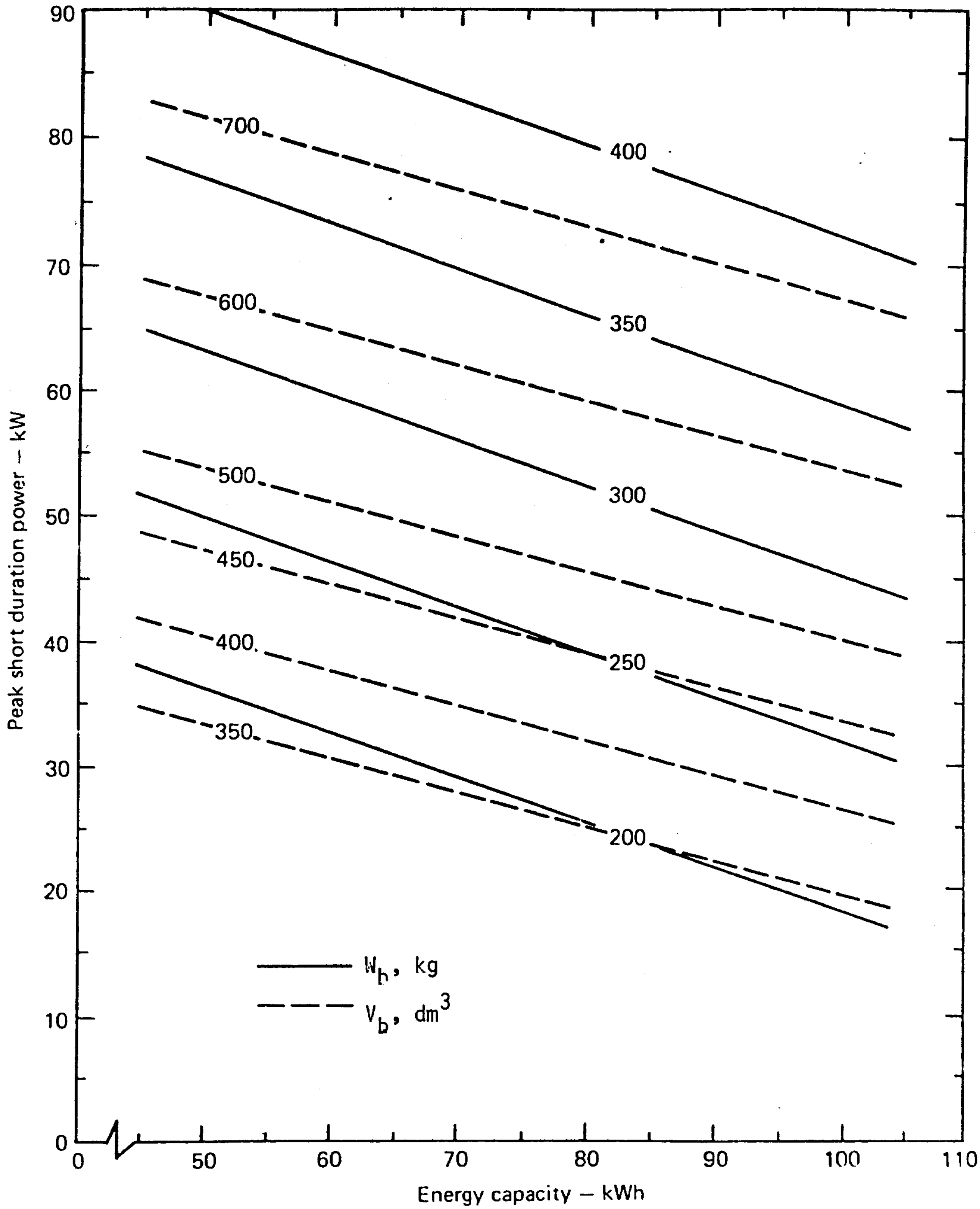

Figure 4. Map of power cell system weight and component volume, for specified peak power and nominal energy storage capacity. Equations (8) and (9) evaluated for $\overline{E}_{Al}$ = 4.25 kWh/kg, p = 6.2 kW/m^2, e_p = 0.96 (nominal conditions), e_p = 1.0 (peak conditions), and n = 4.

In Figure 5, the weight of the battery (of given peak-power and energy content) is plotted against n. A small weight penalty is incurred by increasing the interval between aluminum refuelings from four to ten-fold that of water refuelings. This is a consequence of the high specific energy yield of aluminum (4 kWh/kg-Al and 11 kWh/dm^3-Al).

The specific gravity of the battery (W_b/V_b) varies between 0.5 and 0.6 over the range of design variables shown in Figure 4.

The Sizing and Placement of Components

The volumes of the engine compartments and fuel tanks of two intermediate size automobiles are given in Table 3, along with the volume occupied by the components of aluminum-air power cells. The power cell volumes were determined by equations (8) and (9) and represent the space occupied by the components. The actual space requirements for the power cell system will be somewhat greater when provisions are made for air-circulation (for heat rejection and ventilation) and for accessibility of the components for refueling or maintenance operations. It is reasonable to place the tap-water storage tank in the volume normally occupied by a gasoline tank. The hydrargillite storage tank (a rectangular prism) could be placed in the engine compartment between the cell stack and the passenger compartment, for ready removal as a unit during product discharge. The cell stack could then occupy the upper portion of the engine compartment between the hydrargillite tank and the condenser, with the electrolyte storage tank and crystallizer located directly below. Despite the large available volumes, the geometry and placement of components presents a difficult engineering proglem, if the power cell is to be demonstrated in a conventional automobile. In the long run, however, the volume of the propulsion system is not likely to be a limiting factor in the design of a aluminum-air vehicle.

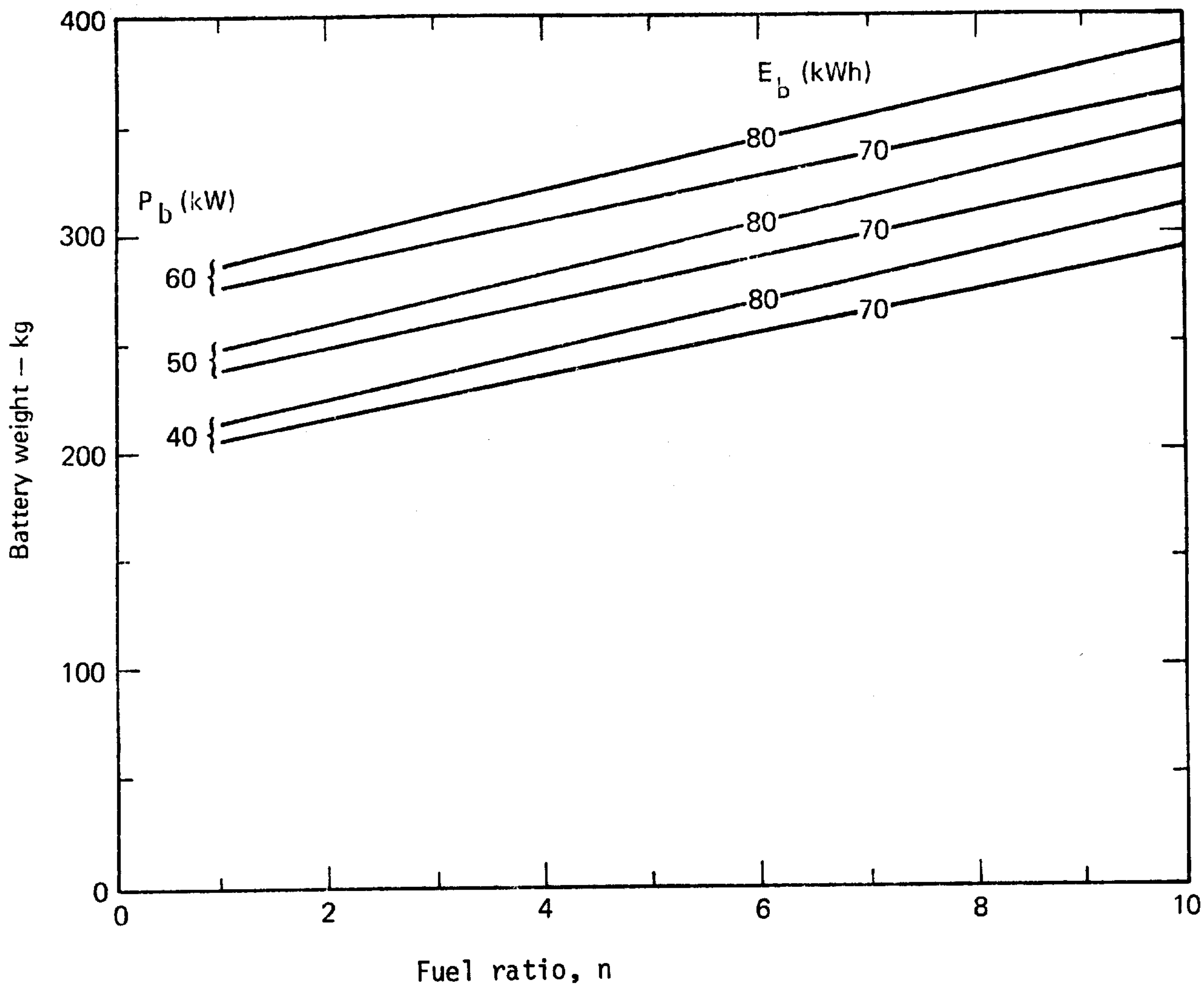

Figure 5. Dependence of power cell system weight on the relative frequencies of aluminum and water recharge. Operating conditions as in Figure 4.

Table 3. Available volumes within intermediate size automobiles, and volumes occupied by aluminum-air power cell components.

	Volumes (dm^3)		
	Engine Compartment (Components in Engine Compartment)	Fuel Storage (Water)	Total
1975 Ford Mustang II	720	60	780
1980 Buick Skylark (X-Body)	575	55	630
40 kW, 70 kWh Power Cell	(410)	(30)	440
50 kW, 70 kWh Power Cell	(480)	(30)	510
60 kW, 70 kWh Power Cell	(550)	(30)	580

REFERENCES

1. J. F. Cooper, "Control of Battery Electrolyte Composition Through Precipitation of Aluminum Trihydroxide: Feasibility Study," Proc. First International Workshop on Reactive Metal Air Batteries, University of Bonn, West Germany, July 9-11, 1979, Lawrence Livermore Laboratory Preprint UCRL-82396, August 1979.

2. R. V. Homsy, "Aluminum-Air Power Cell System Design," Proc. First International Workshop on Reactive Metal Air Batteries, University of Bonn, West Germany, July 9-11, 1979. Lawrence Livermore Laboratory Preprint UCRL-82497-1, August 1979.

APPENDIX

TABLE I: WEIGHTS AND VOLUMES OF BATTERY COMPONENTS

	WEIGHT(kg)	VOLUME(dm^3)
Storage Tanks		
Tap Water (polyethelene, 35 l capacity)	1.32	36.4
Distilled water holding (polyethylene, 10 l)	0.38	10.4
Hydrargillite (75 l)	2.90	78.0
Crystallizer and Electrolyte Storage Unit		
Electrolyte Storage Compartment (20.7 l, high density polyethylene)	0.78	21.5
Electrolyte (for circulation)	25.60	
Crystallizer vessel (polyethylene, 15.5 l)	0.58	16.2
Seed Crystal (40%-vol. of slurry)	15.00	(6.20)[a]
Electrolyte (60%-vol. of slurry)	11.75	(9.30)
Insulation (ca. 5cm thick, 0.1 g/cm^3)	4.02	40.24
External containment vessel walls (corrugated 20 mil steel)	4.05	0.51
Air Intake Funnel, Filter, and Humidifier/Scrubber		
Intake funnel and trunk (paper-wrapped wire)	0.2	3.0
Filter containment vessel and paper filter (based on automotive filter unit)	1.0	7.0
Humidifier/scrubber unit (polyethylene walls; stainless steel spray nozzle)	1.0	7.0
Motors and Pumps		
Drive motor for air and electrolyte pumps (0.9 kW peak; 1.8 kg/kW)	1.64	0.3
Electrolyte pumps (4)	1.81	0.5
Air Pump (1)	1.81	2.0
Water Pump (4 ml/s; gear pump)	0.30	--.[b]
Crystallizer internal circulation pump	0.50	--.[a]
Drive shafts and clutches	2.5	--.[b]

a Weight or volume listings in parentheses or indicated by (a) have been counted elsewhere in the table.

b Indicates insufficient data for useful estimate.

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Crystallizer and Electrolyte Storage Unit		
Electrolyte Storage Compartment (20.7 l, high density polyethylene)	0.78	21.5
Electrolyte (for circulation)	25.60	
Crystallizer vessel (polyethylene, 15.5 l)	0.58	16.2
Seed Crystal (40%-vol. of slurry)	15.00	(6.20)[a]
Electrolyte (60%-vol. of slurry)	11.75	(9.30)
Insulation (ca. 5cm thick, 0.1 g/cm^3)	4.02	40.24
External containment vessel walls (corrugated 20 mil steel)	4.05	0.51
Air Intake Funnel, Filter, and Humidifier/Scrubber		
Intake funnel and trunk (paper-wrapped wire)	0.2	3.0
Filter containment vessel and paper filter (based on automotive filter unit)	1.0	7.0
Humidifier/scrubber unit (polyethylene walls; stainless steel spray nozzle)	1.0	7.0
Motors and Pumps		
Drive motor for air and electrolyte pumps (0.9 kW peak; 1.8 kg/kW)	1.64	0.3
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Drive shafts and clutches	2.5	--.[b]

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b Indicates insufficient data for useful estimate.

	Weight (kg)	Volume (dm^3)
Galvanic Cell Stack	a	148.
Vessel walls, external (reticulated, high density polyethylene, 1cm thick, 0.3 solid fraction, density = 0.95)	5.0	a
Cathode and internal current collector	3.6	a
Cathode support plate - carbon reinforced epoxy $6.6 m^2$, mm thick	9.4	a
Anode support plate (as above)	9.4	a
Interelectrode spacer and flow channel ribs (60-mil nylon, $1.53\ m^2$) 0.15cm thick	2.6	a
Anode current collector	3.3	a
Intercell Electrolyte Tubes (25 m, 2 cm O.D., 1.5 mm wall thickness, high density polyethylene)	2.2	7.9
Intercell Air Tubes (15 m; 3 cm O.D., 1 mm wall thickness, Polypropylene)	1.4	10.6
Condenser	5	20
Miscellaneous (Current busses and intercell connectors; sensors)	15.0	5
TOTAL	134.0 kg	413.6 dm^3

TABLE II: WEIGHTS OF BATTERY REACTANTS AND PRODUCTS AT BEGINNING AND END OF 400 km CYCLE

	WEIGHT (kg)		
	INITIAL INVENTORY	TRANSFERRED FROM ENVIRONMENT	FINAL INVENTORY
Aluminum			
Consumed Galvanic Reaction (95%)	15.96	0.0	0.0
Consumed Parasitic Reaction (5%)	0.84	0.0	0.0
Reserve	16.8	0.0	16.8
Excess For Subsequent 400-km Cycles[a]	25.2	0.0	25.2
Water			
Galvanic Reaction With Al (95%)	15.98	0	0
Parasitic Corrosion Reaction With Al (5%)	1.683	0	0
Loss In Vapor From Condenser (32^{o}C)	8.76	-8.76	
Gained From Air Intake (27^{o}C, 50% relative humidity)	0	3.31	3.31
Entrapped in $Al(OH)_3$ (16 g/g-$Al(OH)_3$)	2.40	0	2.40
Reserve	6.40		6.40
Hydrargillite	0	0.0	48.57
Hydrogen[b]			
Lost by venting	0	0.094	0
Oxygen[b]			
Gained from air intake	0	14.20	0
TOTAL	94.0	8.70	102.7

Condition: stoichiometric air flow factor, 4.88.

a. average assuming 4 cycles of 400 km between aluminum refueling.

b. weights of hydrogen and oxygen included in entries for water and hydragillite, respectively.